Searches for New Physics

(Theoretical Overview)

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Outline

- Physics Beyond the Standard Model?
- Supersymmetry
- Extra Dimensions
- New Forces and Top
- Outlook

Beyond the Standard Model

- Why search for physics beyond the Standard Model?
  - The Standard Model does a very good job of describing data from experiments to date.
  - Some few puzzles remain (such as *Z*-*b*-*b* couplings), but none are very significant.
- The Standard Model is an "effective theory", meaning it is valid for a range of energies, but not to arbitrarily high energies.
  - Gravity (needs to be included somehow at or before $\mathbf{M_{Pl}}$).
  - Couplings get strong (i.e., $\mathbf{Y_t \sim 4\pi}$ at $\mathbf{10^{17}}$ **GeV**).
  - Higgs Mass is highly sensitive to high energy physics.
- Without knowing the theory behind it, we can't predict exactly where or how it will give way to new physics, but we can use what we do know about it to predict where it must break down, and to propose models which address its short-comings.

Hierarchy Problem

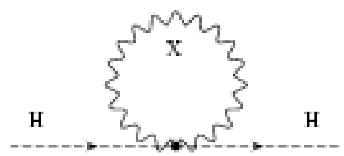
- The sensitivity of the Higgs "mass" to high energy physics is the hierarchy problem.
- The Higgs potential has a dimensionful ("mass") term and dimensionless ("quartic") term:

$$V_\Phi = \lambda \left(|\Phi|^2 - v^2 \right)^2 \qquad M_W = g\, v$$

  - The Higgs VEV, and thus the W/Z masses are linearly related to v.
  - So $\lambda \mathbf{v}$ can't be much bigger than M_W and M_Z.
- Now imagine that there is some heavy physics that couples to the Higgs.
  - Heavy gauge bosons left-over from a GUT theory.
  - Right-handed neutrino needed in the seesaw theory of neutrino masses.
  - These examples couple to the Higgs directly.
  - All particles couple to it through gravity.

Naturalness

- So what does this hypothetical heavy particle do to v^2?
- It corrects it through loops. At one loop, in the specific case of a GUT gauge boson, the correction looks like:



$$\frac{g^2}{16\pi^2} M_{GUT}^2$$

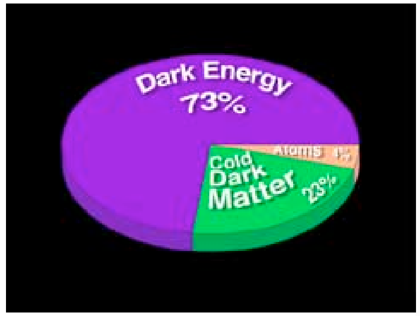
  - The GUT scale has appeared as the mass of the vector boson.

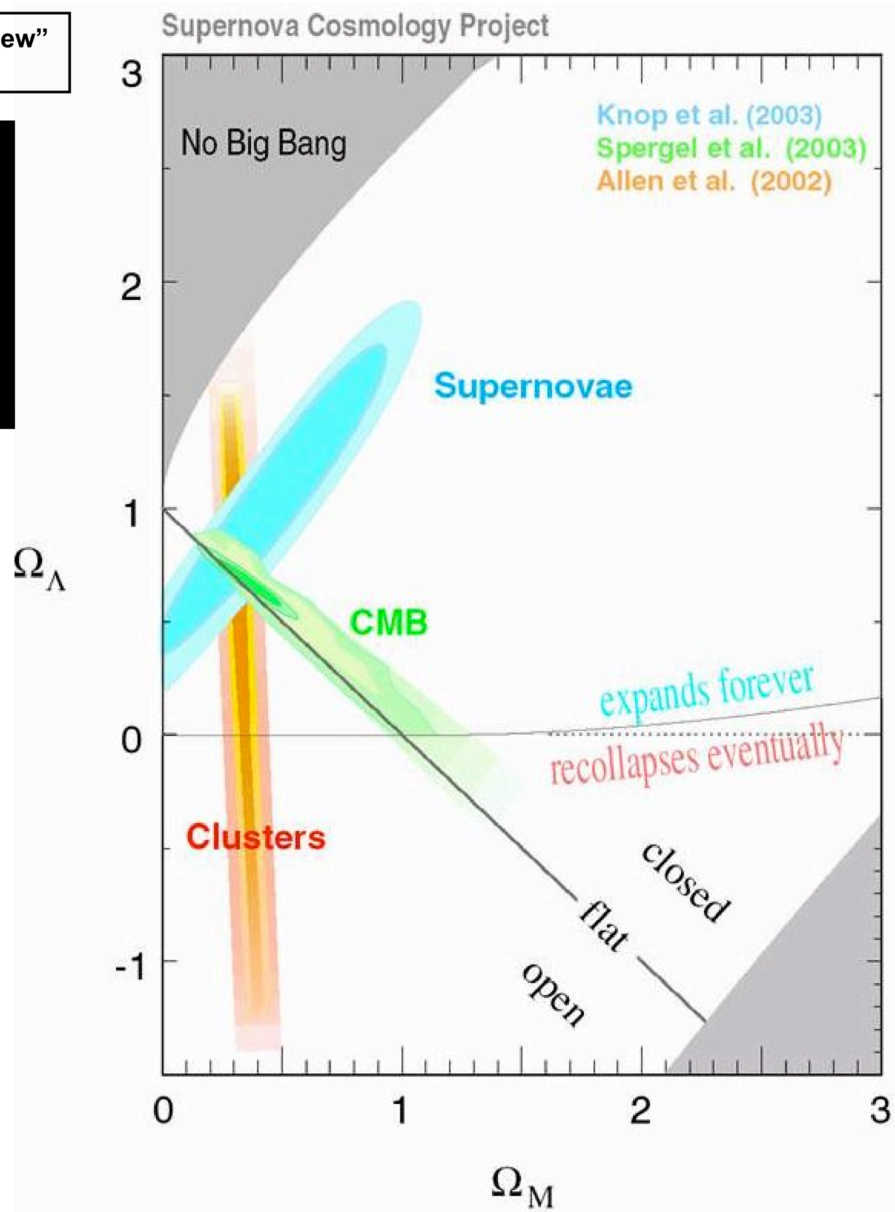
$$v^2 = v_0^2 + \frac{g^2}{16\pi^2} M_{GUT}^2 + \ldots$$

- In perturbation theory, the v^2 measured in experiments (for example, when we measure M_W at LEP or the Tevatron) is the sum of the tree level piece plus all of the higher order corrections:
  - Here we see the issue: the loops should be small, but if the masses that go into the loops are large, then they are huge.
  - But we don't know what the tree-level piece (v_0^2) was…
  - Unless it is of the same order as v^2 itself, this will be a fine-tuned cancellation, asking for something to explain it.

Dark Matter

"Cold Dark Matter: An Exploded View"
by Cornelia Parker



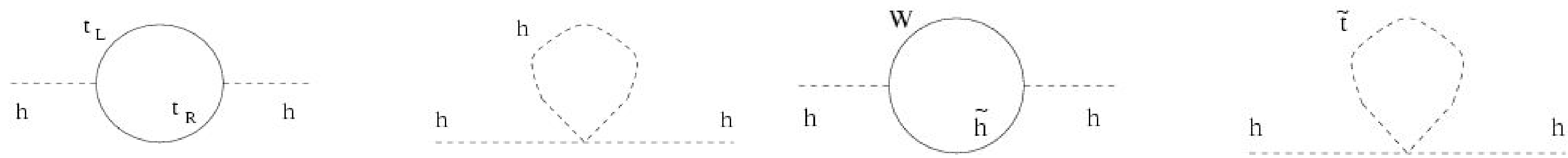


Measurements from Supernovae, the CMB, and structure formation indicate that most of the universe should be made out of stuff we've never seen. In particular, dark matter hints at the existence of some exotic neutral stable heavy particle.

The SM has nothing that can play this role. So it falls to theories beyond the SM to explain it. Ultimately, to discover what DM is, we need to produce it at colliders and measure its properties directly.

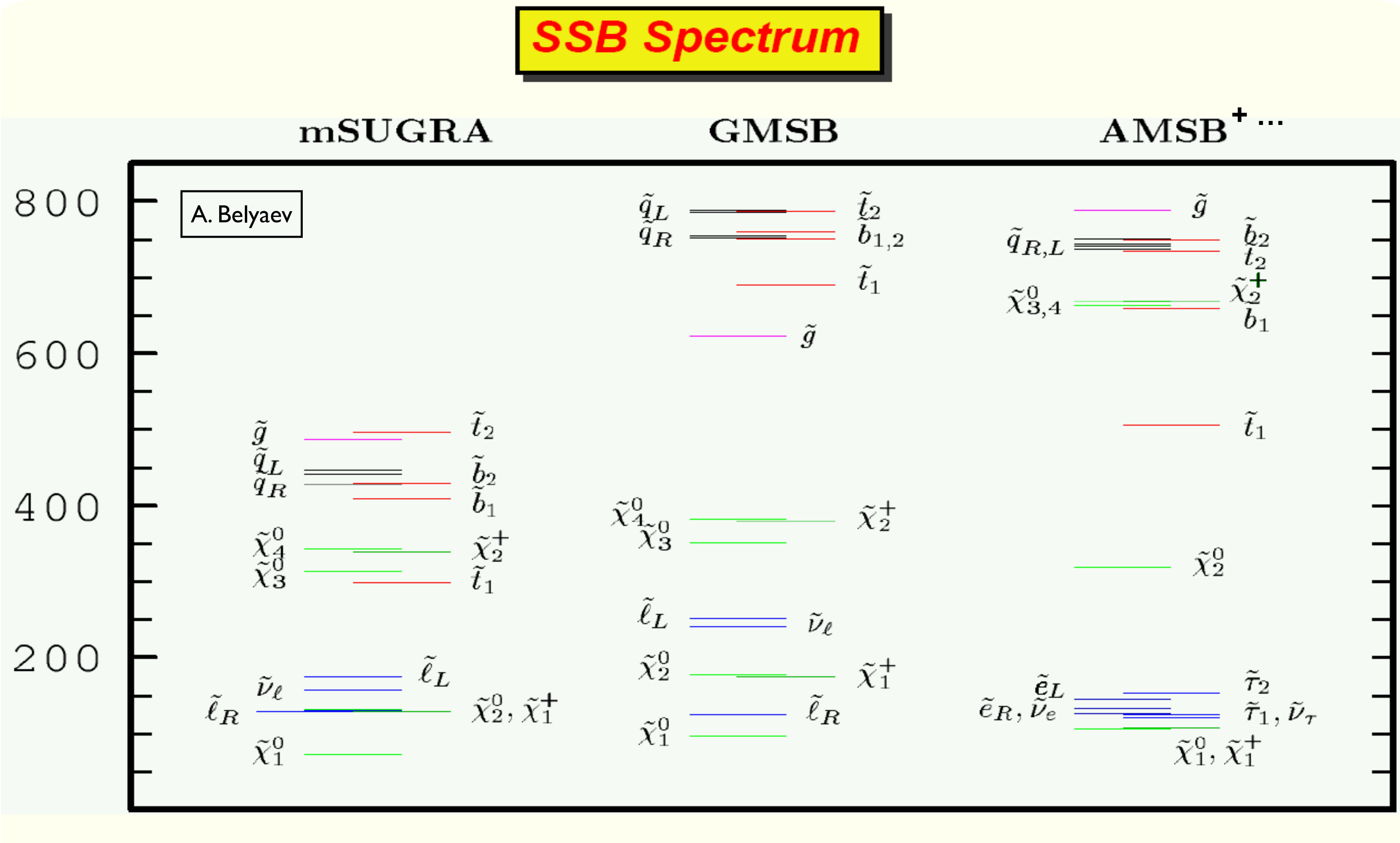
Supersymmetry

- Supersymmetry is the best-motivated and best-studied solution to the hierarchy problem.
- The super-partners cancel exactly the big contributions to v^2.

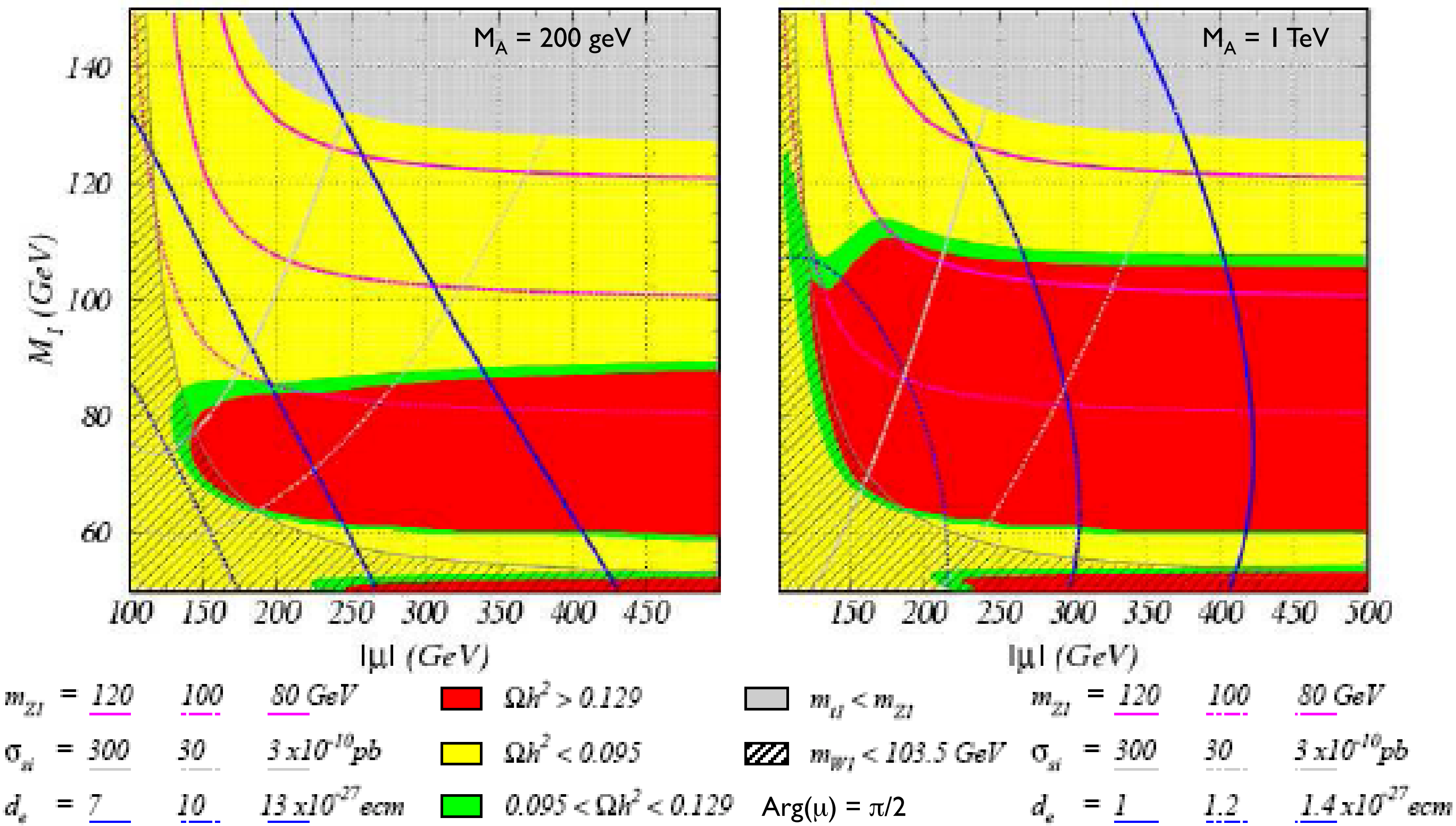


- As an added bonus, most SUSY theories contain a lightest super-partner which is neutral and stable – a dark matter candidate!
- SUSY has a lot of model parameters (all related to how we break it).
  - We have some theoretical guidance as to the rough features, based on how the masses evolve from high energies to low energies, but they could be fallible.
- Many ideas for SUSY-breaking are on the market:
  - **mSUGRA**: Gravity mediates SUSY breaking to the MSSM super-partners.
  - **GMSB**: Gauge interactions mediate SUSY breaking – Solution to the flavor problem.
  - **AMSB**: SUSY breaking is transmitted via the super-Weyl anomaly.
  - **$\tilde{g}$MSB:** Extra dimensional gauge interactions transmit SUSY breaking.
  - **"Orbifold"**: SUSY breaking by extra dimensional boundary conditions.
  - **????** :Theorists are constantly looking for new ways to mediate SUSY breaking!

SUSY Spectra



Supersymmetric Dark Matter

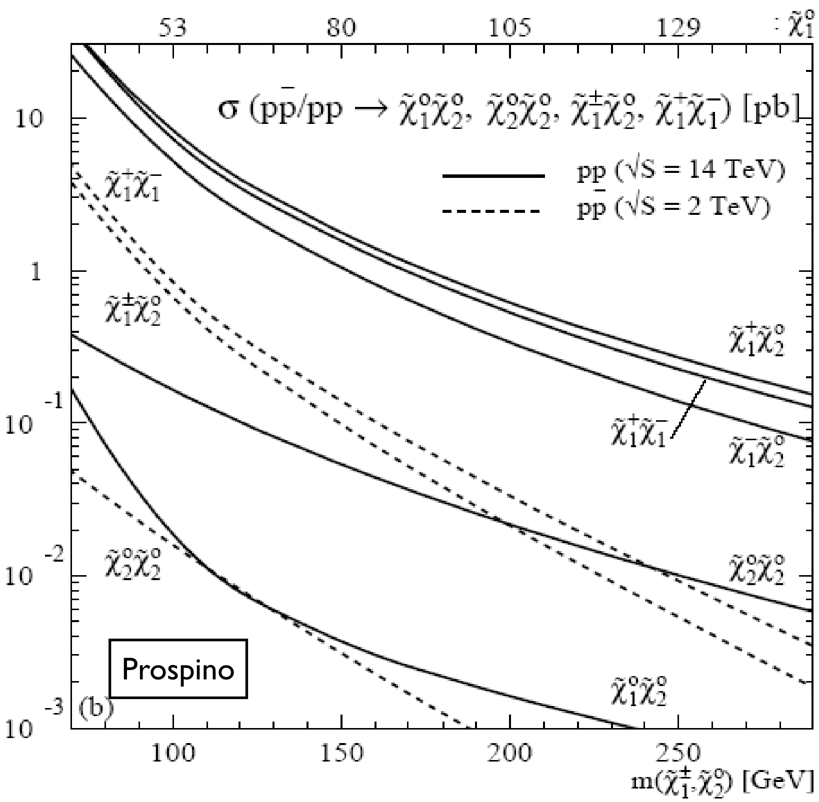


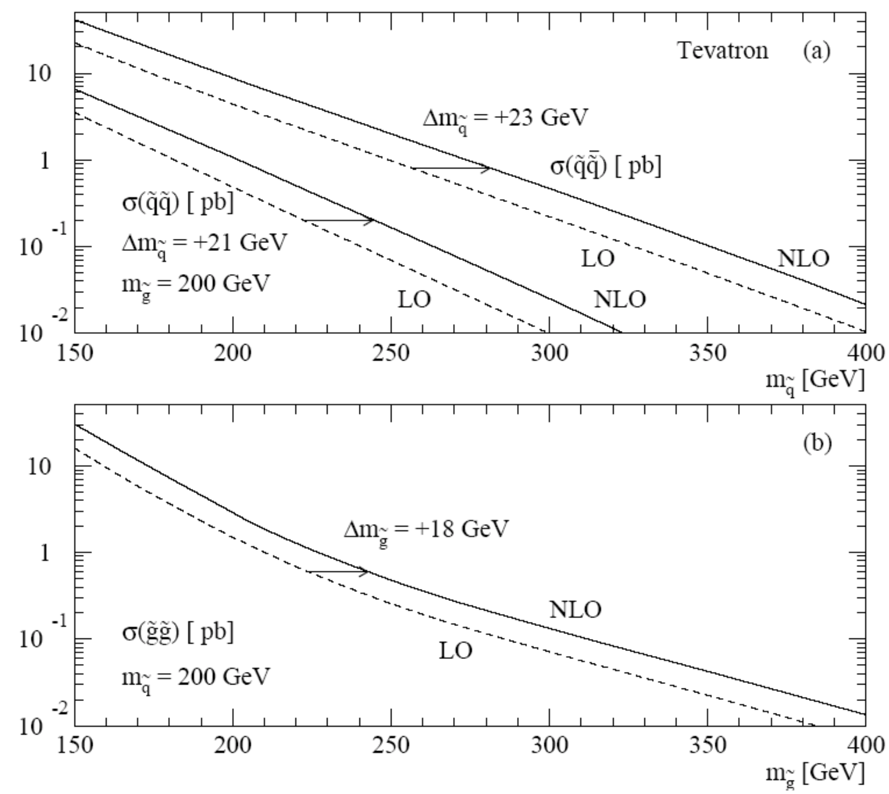
Balazs, Carena, Menon, Morrissey, Wagner hep-ph/0412264

SUSY at Colliders

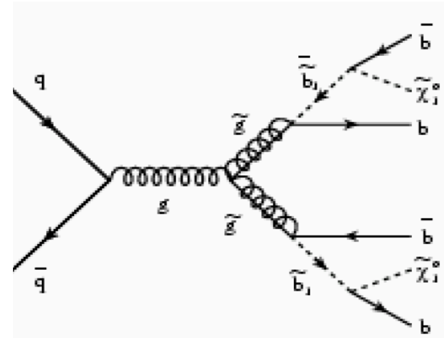
- If nature is supersymmetric as a solution to the hierarchy problem, super-partners should have masses no larger than several hundred GeV.

- Hadron Colliders can copiously produce colored super-partners, which will cascade down to the Lightest Supersymmetric Particle. However, we expect these are the heaviest and thus cross sections for neutralinos and charginos may be more significant. Tevatron has a unique perspective on these electroweakly interacting particles because it is a $p\bar{p}$ collider. LHC's large center of mass energy allows it to produce the strongly interacting super-particles, resulting in complicated cascade decay signatures.

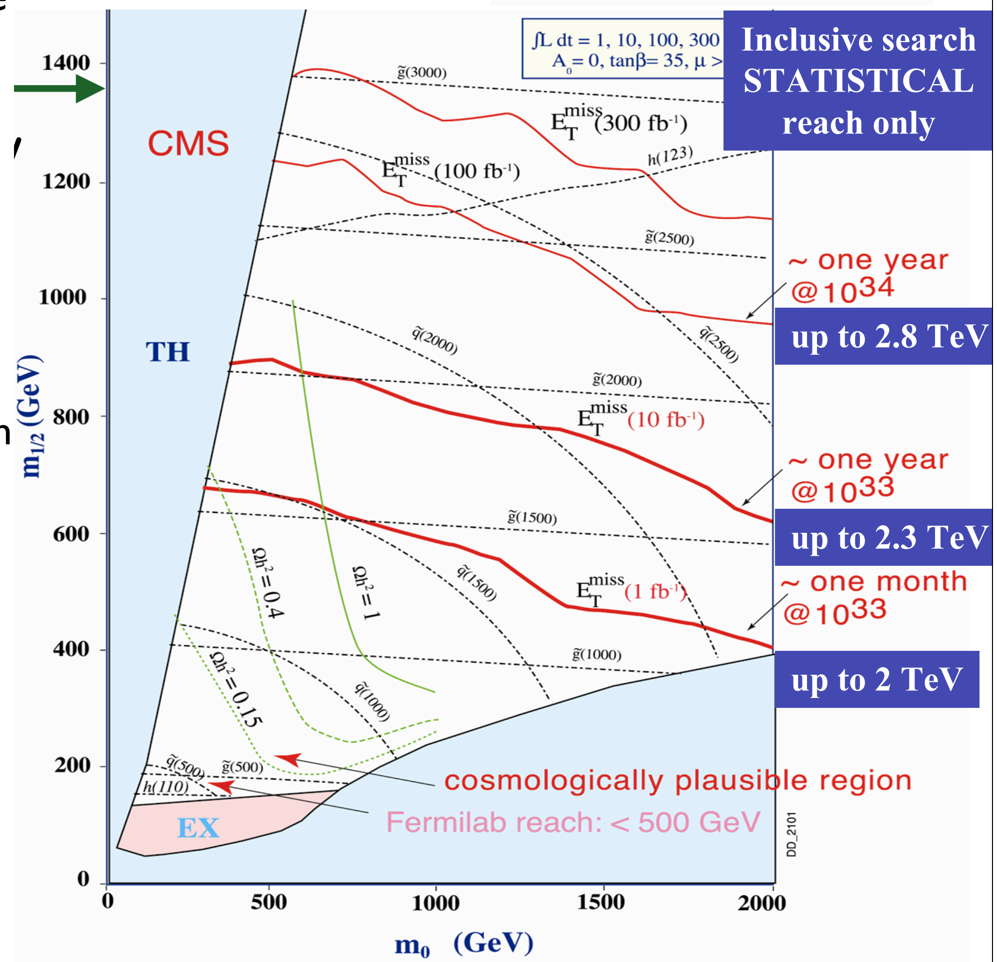




SUSY Signatures



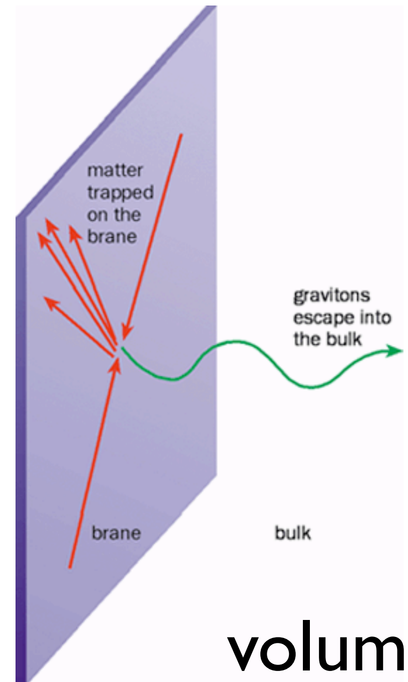
- Since the strongly interacting super-partners are most copiously produced at a hadron collider, but are also expected to be among the heaviest of the SUSY states, signatures are often complicated.
- Cascade decays through several intermediate resonances are often dominant, leading to high multiplicity final states with a lot of kinematic structure.
- Missing energy is the common theme which runs through most signatures, provided R-parity is conserved and the LSP is neutral.
- In fact, missing energy is a generic WIMP signature even if the WIMP is not supersymmetric…
- Some models have unique features. For example, GMSB often has a gravitino LSP leading to extra γ's. Some models have long-lived charged τ 's.



“Large” Extra Dimensions

(Also known as Arkani-Hamed, Dimpoulos, and Dvali, or **ADD** Extra Dimensions)

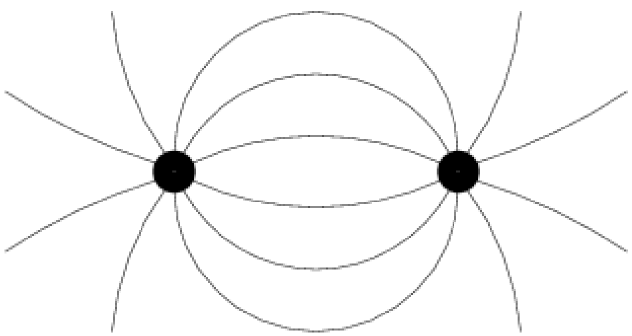
- Other ways to solve the hierarchy problem use extra dimensions.
- The simplest version has an extra dimension that gravity can enter, but all of the SM is stuck on a wall (or “brane”) in the extra dimension.
- The hope is that at the TeV scale, string theory will take over. Gravity only “seems” weak because it is diluted in the extra dimension.



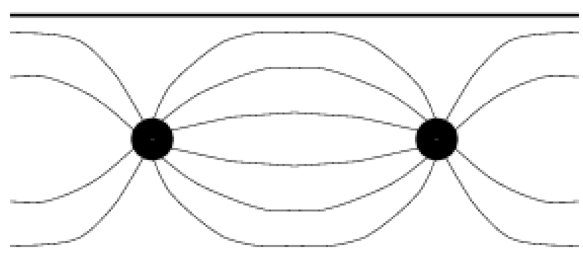
volume

$$M_{Pl}^2 \; ; \; R^n M_*^{n+2}$$

~ TeV!



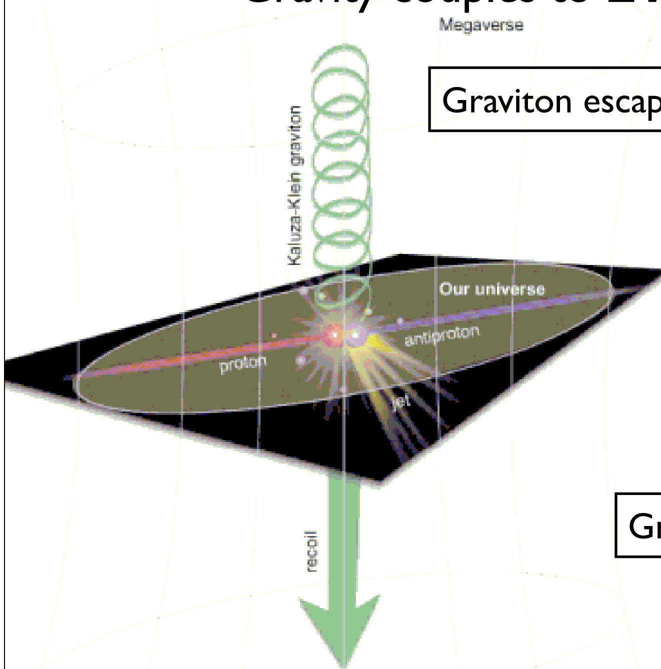
Gravity field lines spread into the bulk



SM force confined in the brane

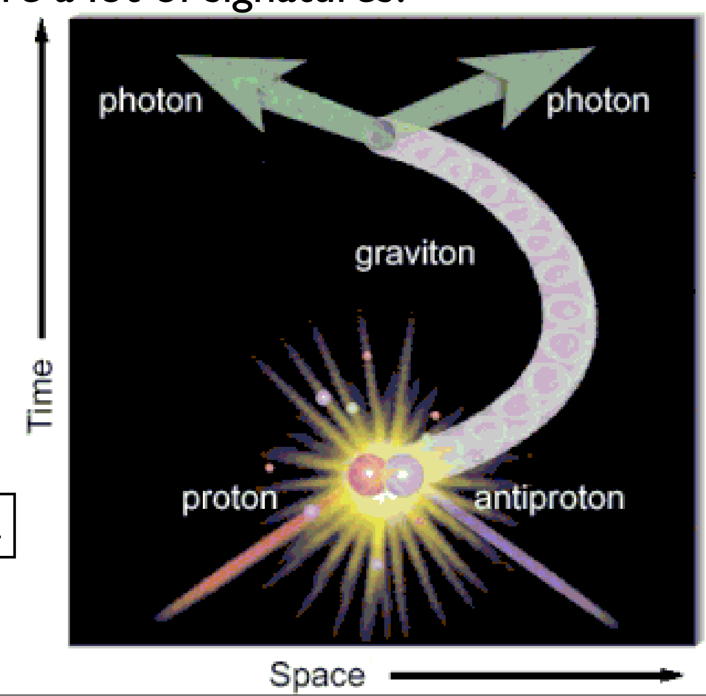
ADD Signatures

- The extra-dimensional gravitons look like a "tower" of massive gravitons to those of us stuck in four dimensions.
- The masses are evenly spaced n / R (R is the radius, n an integer).
- For R around 1 mm, the spacing is in **keV**. So they are *so* tightly spaced, that they almost look continuous – very different kinematics from SUSY.
- Individually, each graviton is coupled like $1/M_{Pl}$. Relevant effects at run II come from the fact that there are so many graviton modes we can produce.
- Gravity couples to **EVERYTHING**! So there are a lot of signatures!



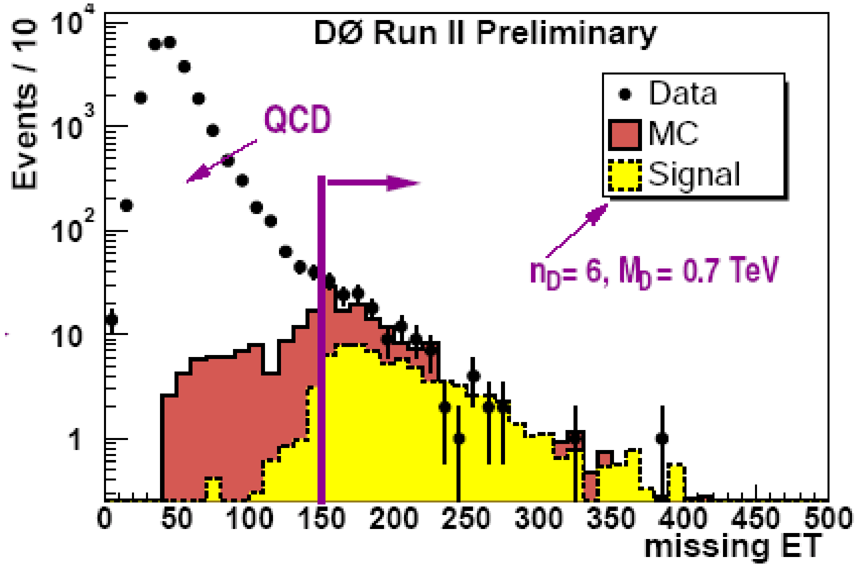
Graviton escapes from the brane.

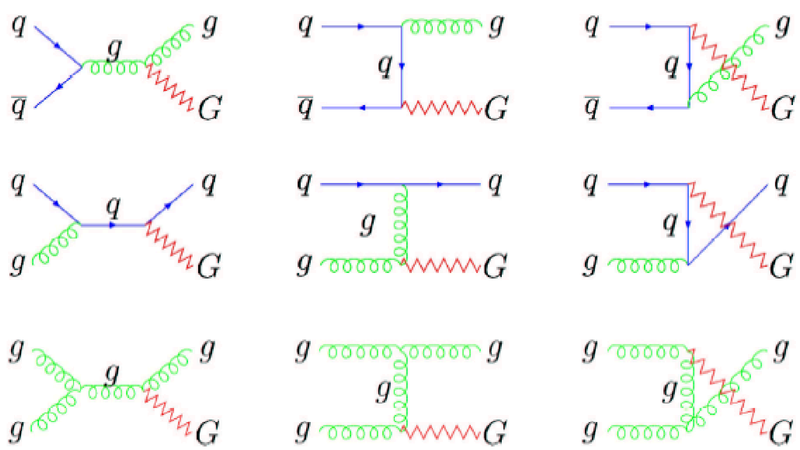
Graviton comes back to the brane.



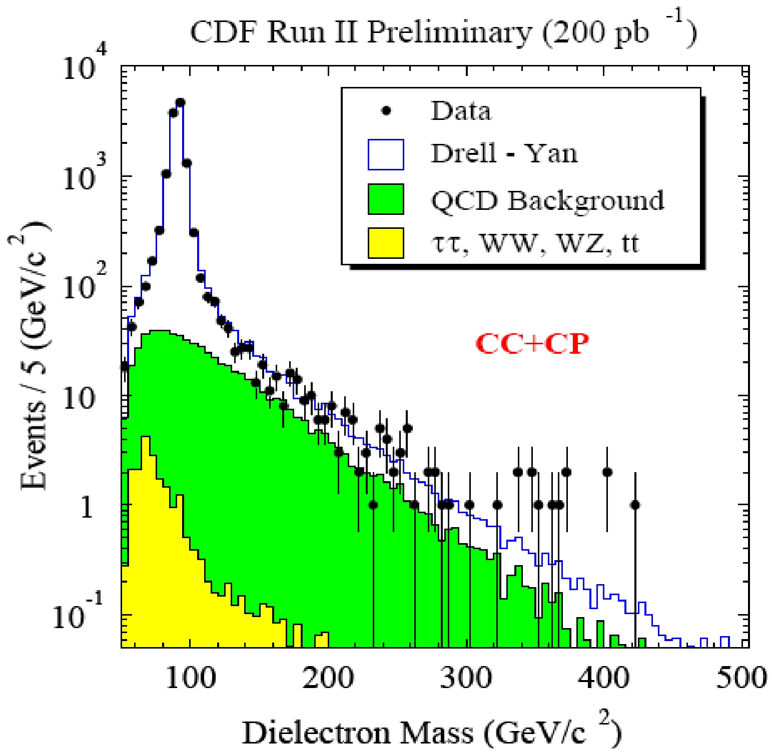
KK Gravitons, Real and Virtual

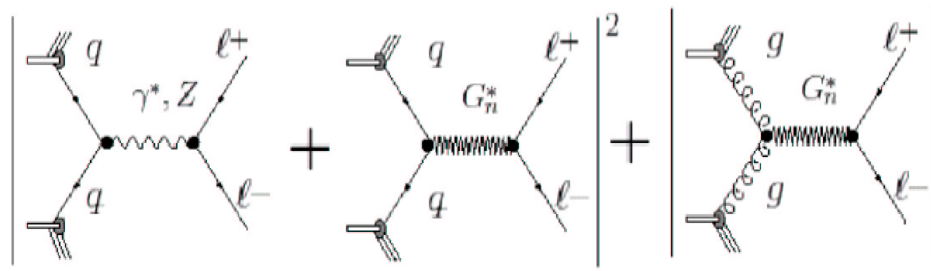
DØ jet+$\not{E}_T$ Signature (85 pb^{-1}):





CDF dielectrons:

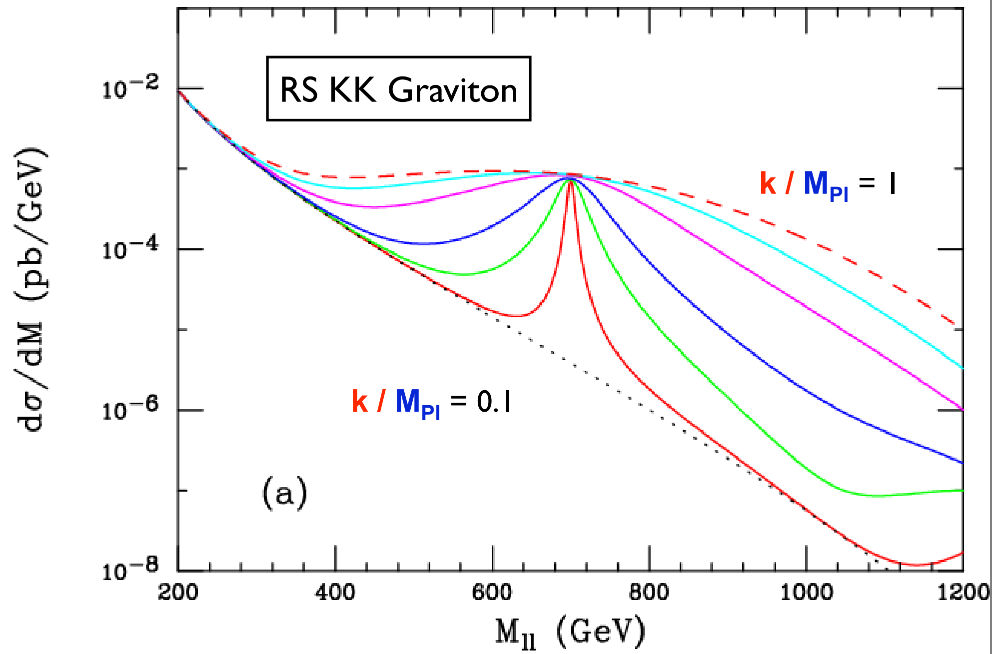




Randall-Sundrum

(also known as a **Warped** or **ADS$_5$** Extra Dimension)

- Another brane world scenario has warping in the extra dimension.
- A warped background radically changes the graviton properties.
  - They couple more **strongly** to the SM, and have large masses with **TeV** spacing. So they are produced copiously, and look like resonances.
- Variations also have gauge fields and/or fermions in the bulk. All have very interesting properties.
  - Bulk gauge fields have KK modes looking like: **Z', W', g'**.
  - Grand unification is natural.
  - KK **XY** bosons are leptoquarks!

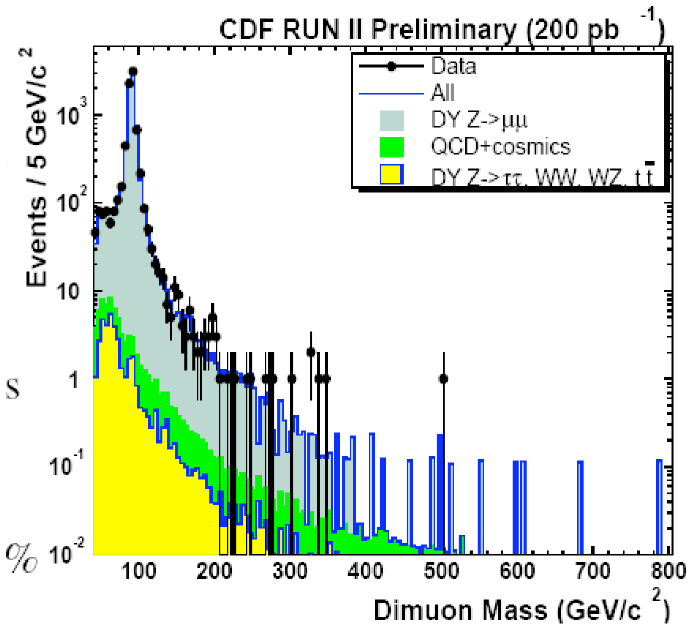


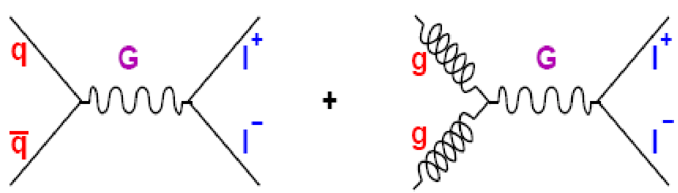
Davoudiasl, Hewett, Rizzo, PRD63, 075004 (2001)

Dominant decay mode depends on what is on the brane or in the bulk – most **model-independent** choices actually **W^+W^-/ZZ/tt**

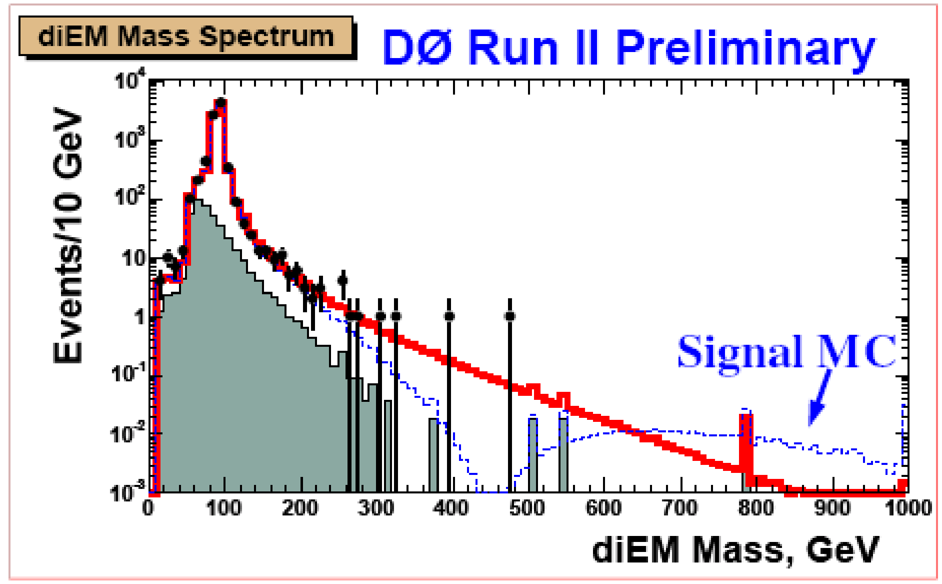
RS KK Modes:

RS Graviton decaying into $\mu^+\mu^-$





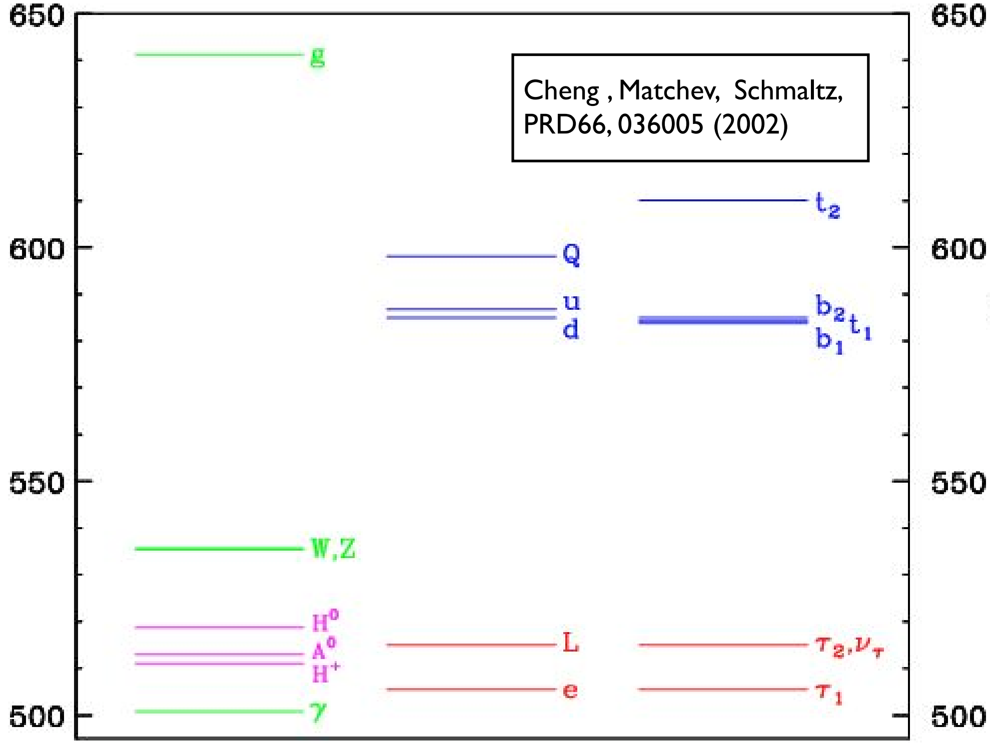
KK "Z'" decaying into e^+e^-

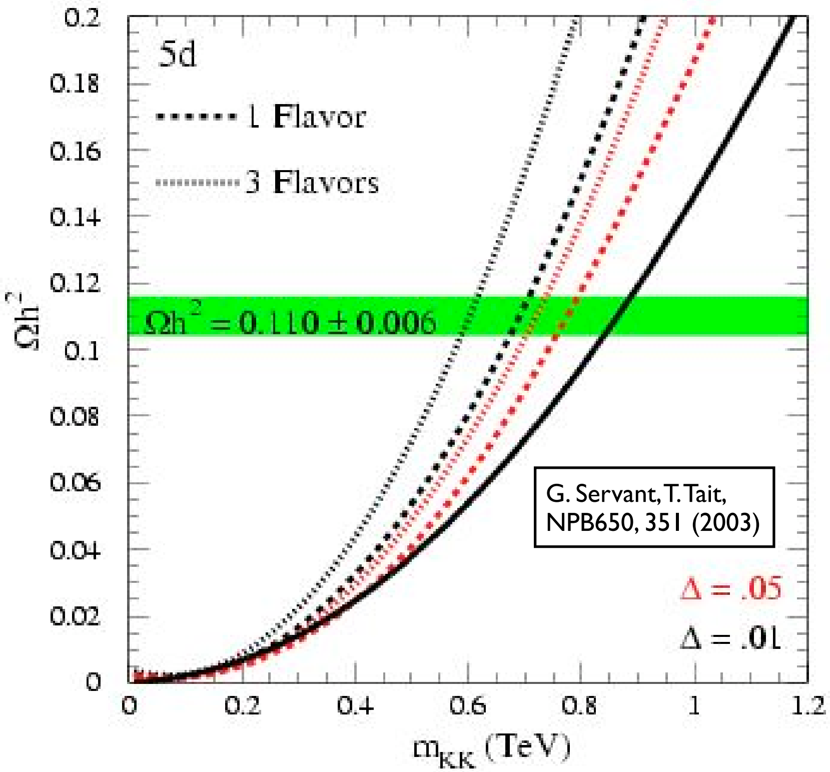


Note the signal interferes with the SM Contribution, leading to a dip as well as excess…

Universal Extra Dimensions

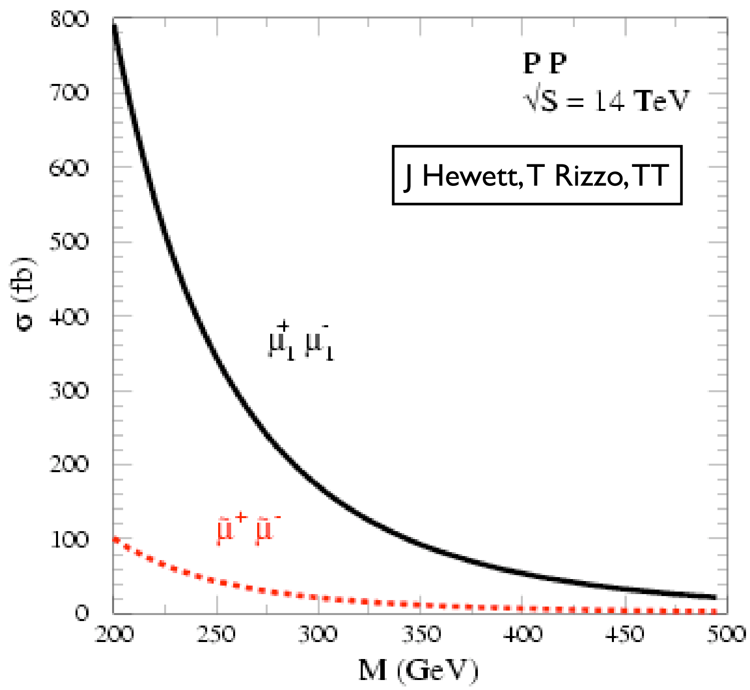
- A final type of extra dimension has no branes at all: all of the SM is living in the extra-dimensional bulk.
- This results in a translational invariance, leading to (approximate) conservation of momentum flowing in the extra dimension.
- The result is a stable Lightest Kaluza-Klein Particle, which provides a dark matter candidate.
- Estimates of the relic density in the case in which it is a KK mode of the hyper-charge boson favor masses in the range of several hundred GeV.

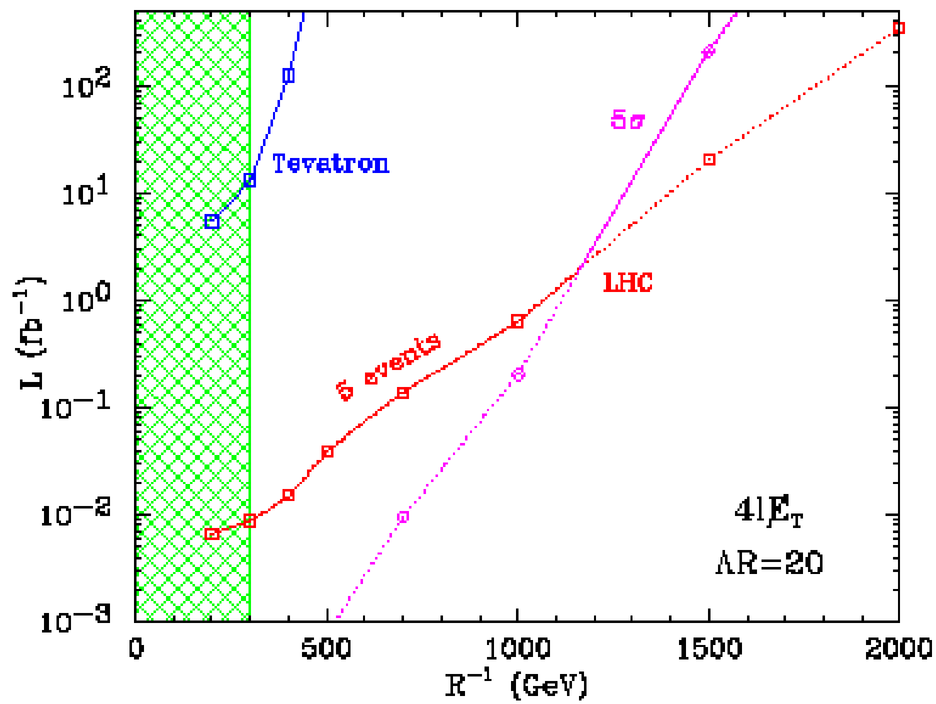




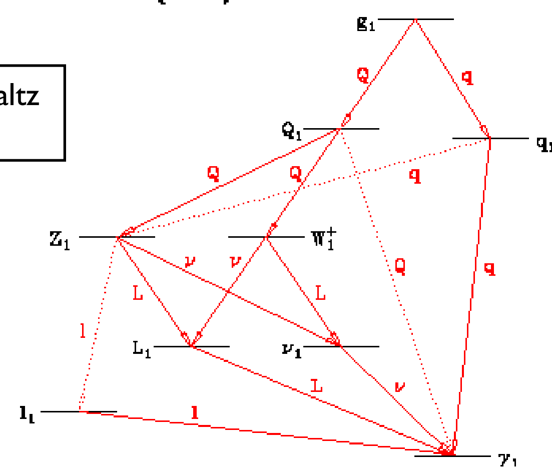
Universal Extra Dimensions

- The "SUSY" of extra dimensions!
    - KK modes must be pair-produced, and decay into the LKP: missing energy.
    - There is an entire tower of KK modes and they have the same spin as their SM counter-parts.
    - Can we tell SUSY from UED?



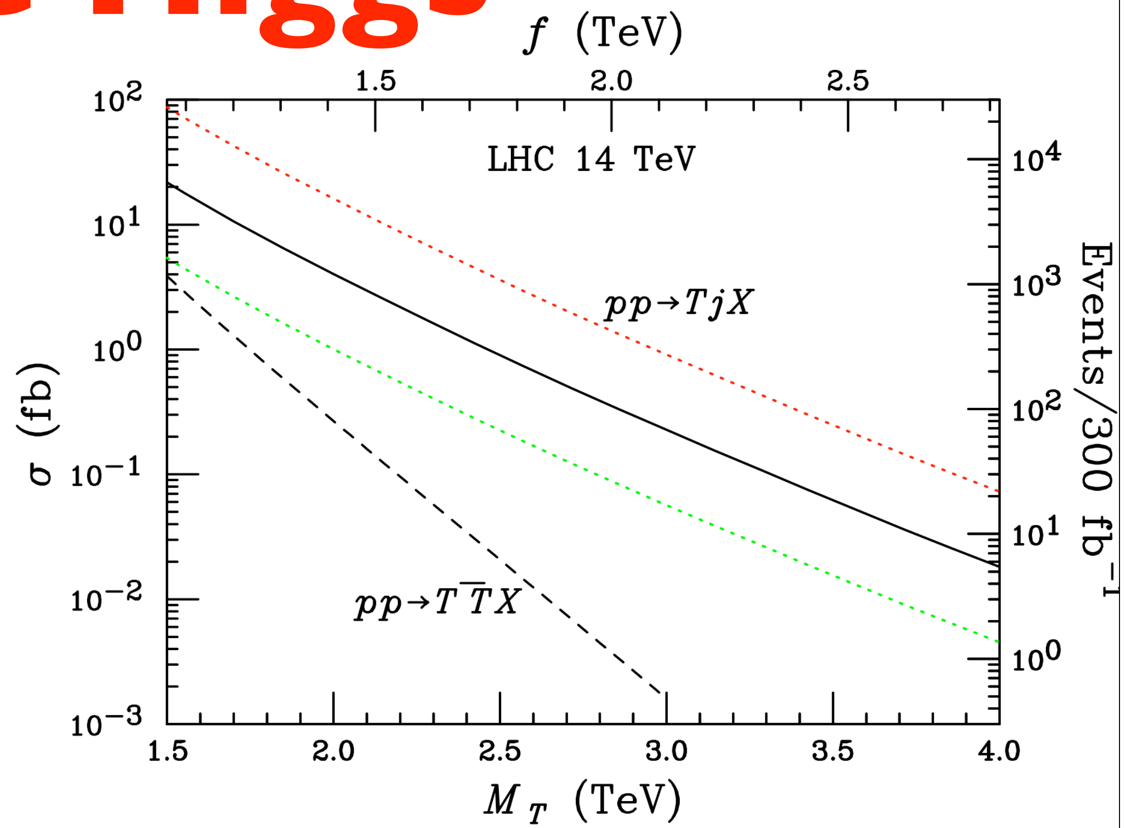


Cheng, Matchev, Schmaltz
hep-ph/0205314

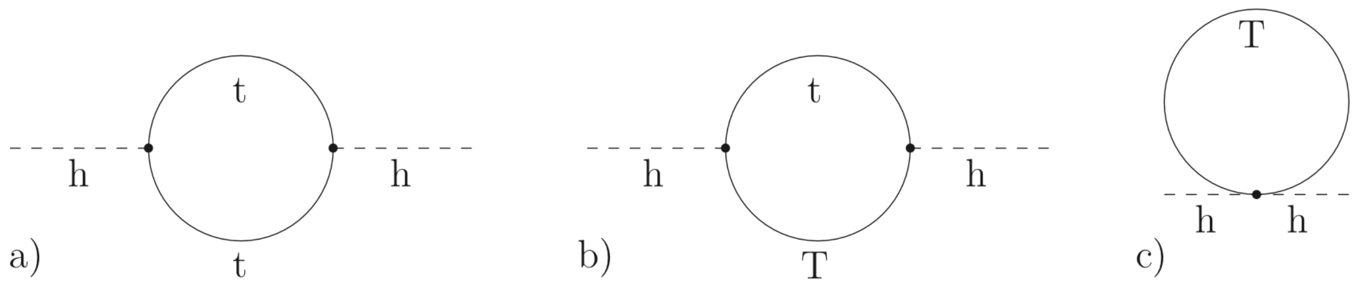


Little Higgs

- Little Higgs theories protect the Higgs mass at one loop by conjecturing that the Higgs is a pseudo-Goldstone boson from the spontaneous breaking of a global symmetry.
- Quadratic divergences cancel at one loop by adding new particles of the same spin as the SM, leading to Z's, t's, ...
- Many variants exist. The most compelling examples have a T-parity which forces the new particles to couple in pairs, and allows the lightest one to be stable and thus a dark matter candidate.

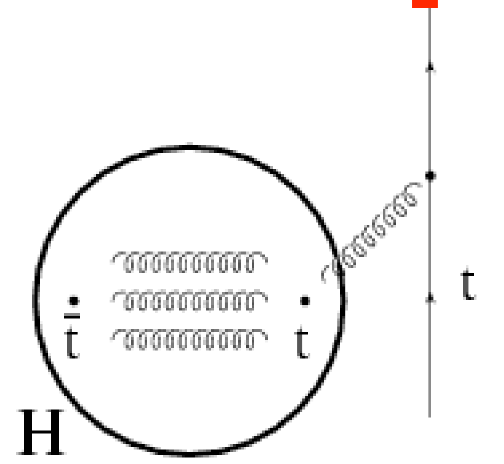


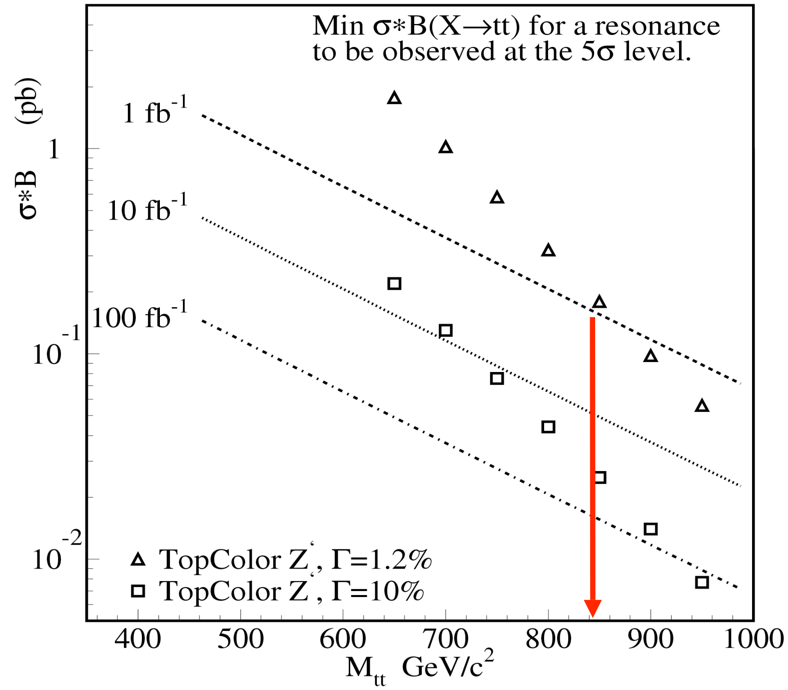
[Han, Logan, McElrath, Wang, 2002]



New Physics and Top

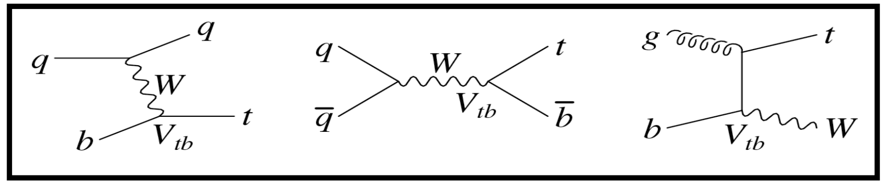
- Why is the top so heavy? Top-color tries to answer this by proposing that the Higgs is actually a bound state of top quarks.
- It solves the hierarchy problem because there are no fundamental scalar particles – the Higgs is natural somewhat like the pion is.
- A new strong force (top-color) forms the Higgs as a bound state of top.
- The heavy "top-gluons" (**g'**) carry color, so can be produced at Tevatron. They like to decay into top and bottom quarks.
- Top is heavy because the Higgs "remembers" that it is made out of top quarks – and couples strongly to them through the top-gluons.
- Variations also have **t'**, **b'**, **Z'** and two Higgs doublets (like SUSY Higgses).

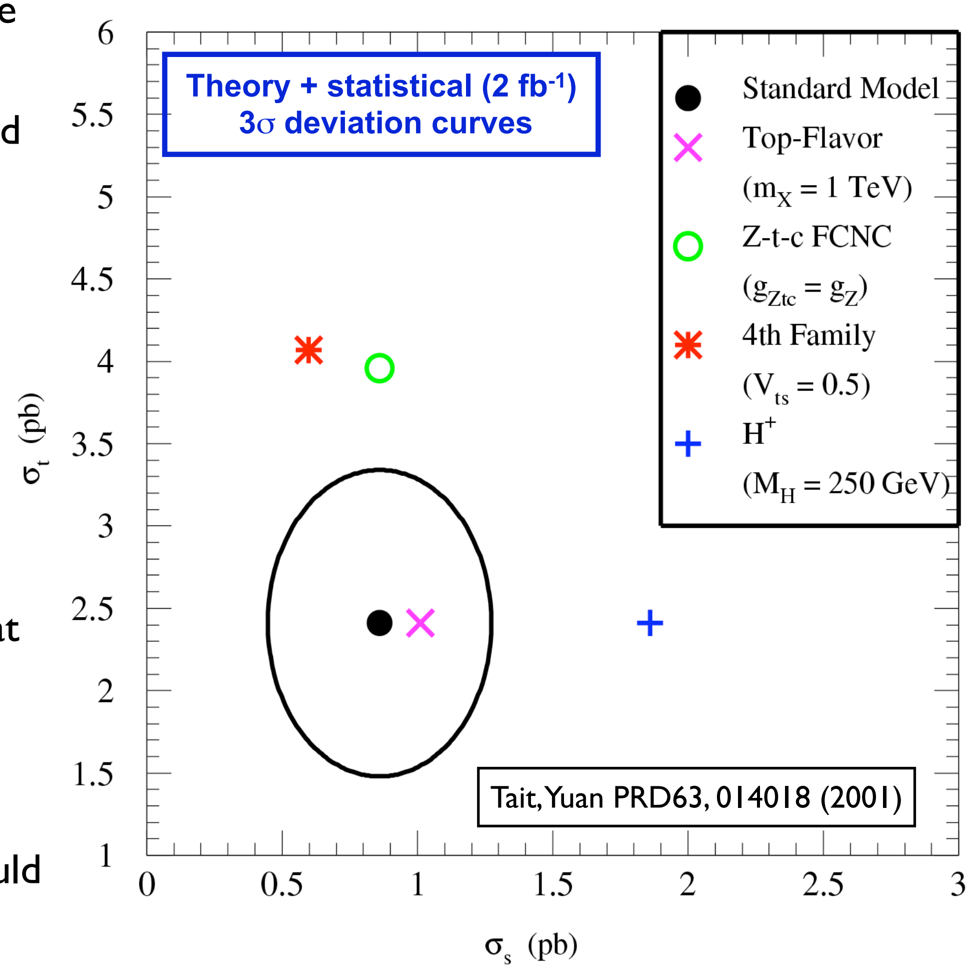




Single Top

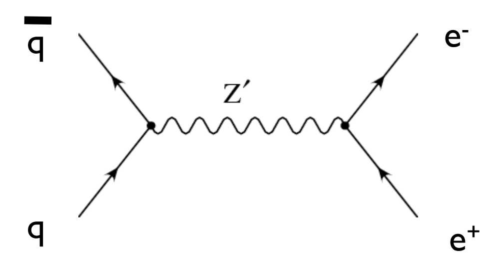
- Single top: the weak interactions of top!
  - Large m_t indicates top is a natural laboratory for EWSB
  - Single top is a direct measurement of the weak interactions
  - V_{tb} can be measured to **5%** (theory limited – Expt limits are ~**2%**).
  - Three Production modes at hadron colliders
    - T-channel mode: largest at both Tevatron and LHC
    - S-channel mode: sizable at Tevatron, very difficult at LHC.
    - tW associated production: hopeless at Tevatron, can be done at LHC.
    - Each mode is sensitive to different kinds of physics beyond the SM.
- Single top is the one thing the Tevatron should see by the end of run II, that has never been seen before!

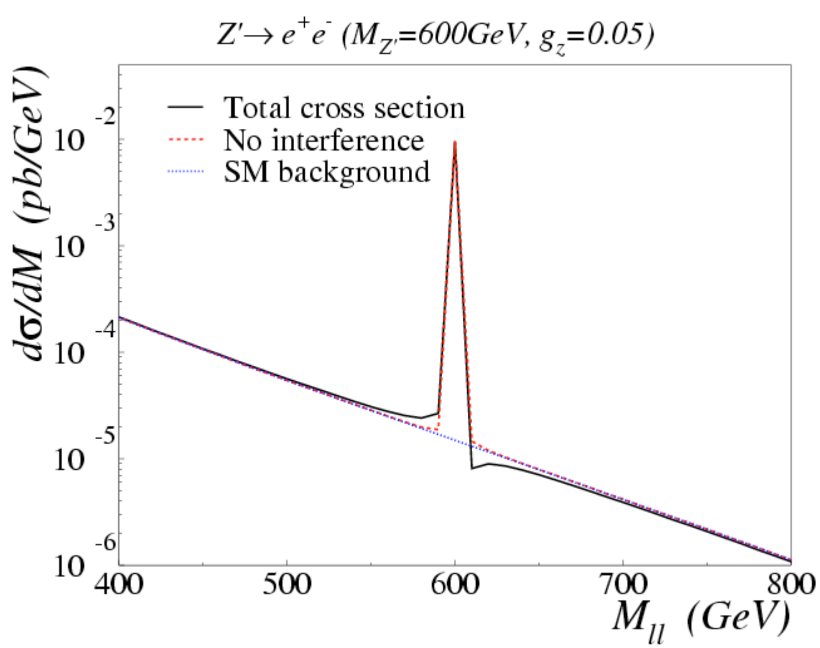


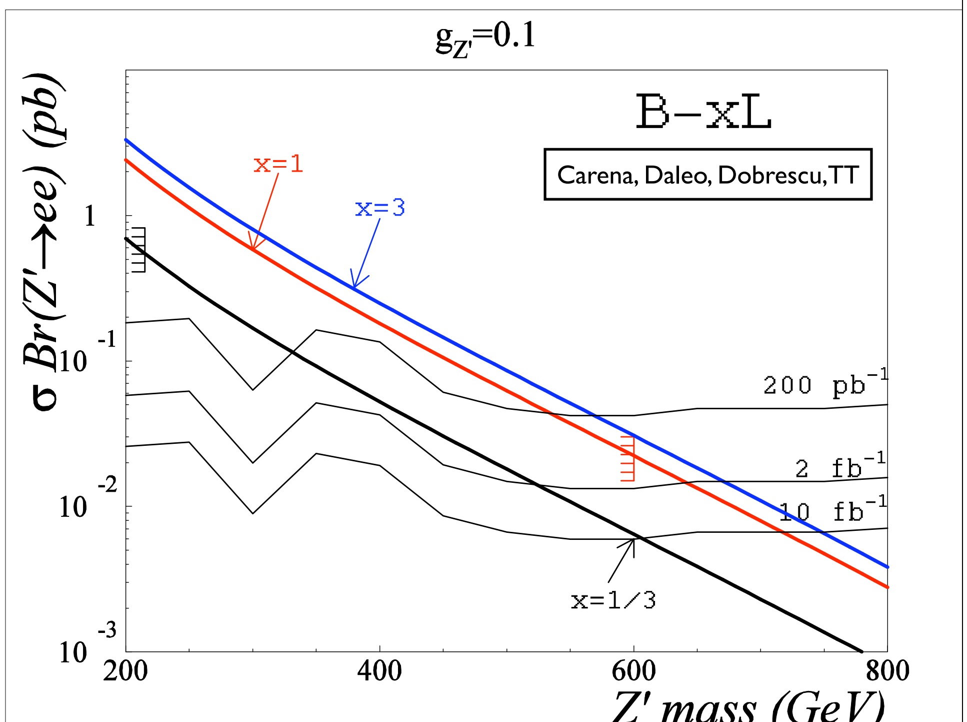


Z’

- New gauge forces appear in many extensions of the SM. Since we really have no evidence that the four forces we know are the only ones, this kind of analysis can be thought of as the question: “Are there new interactions beyond those we know?”
- The usual analyses focus on Z’ decaying to e^+e^- or $\mu^+\mu^-$.
- Great decay modes for the near future would be $\tau^+\tau^-$, $b\bar{b}$, $t\bar{t}$.







Outlook

- The Standard Model works well right now, but it is ready to be replaced!
  - Hierarchy Problem
  - Dark Matter
- **Hadron Colliders** push the energy frontier, and are the places where we expect to see the first glimpses of the new theory.
- **Whatever** that underlying theory is, it will radically change the way we think about particle physics and cosmology.
- I discussed some popular ideas in:
  - Supersymmetry
  - Large Extra Dimensions
  - Warped Extra Dimensions
  - Strong Dynamics
- Right now Tevatron and very soon the LHC, should reveal the nature of Electroweak symmetry breaking and the identity of dark matter!

Supplementary

“Stable” Super-partners

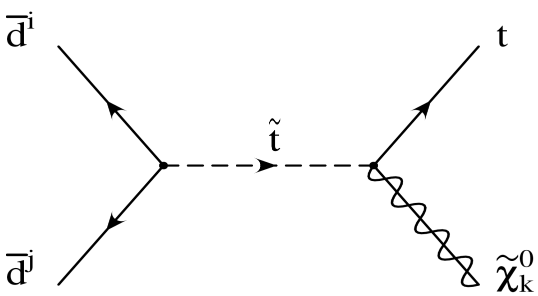
- Some SUSY theories predict that some super-partners may be approximately stable
  - GMSB with a gravitino LSP and a stau NLSP
  - Some extra-dimensional theories (usually stop)
  - The dreaded light gluino and sbottom scenario
- These are particularly nice because they are very different searches from traditional SUSY signatures.
- A popular way to break SUSY is in an extra dimension with an “orbifold”. This usually results in very highly degenerate super-partners and is a great motivation for this kind of search.
- Non-SUSY models can also produce long-lived particles, and they are of obvious interest to cosmology since they will affect the evolution of the universe at early times.

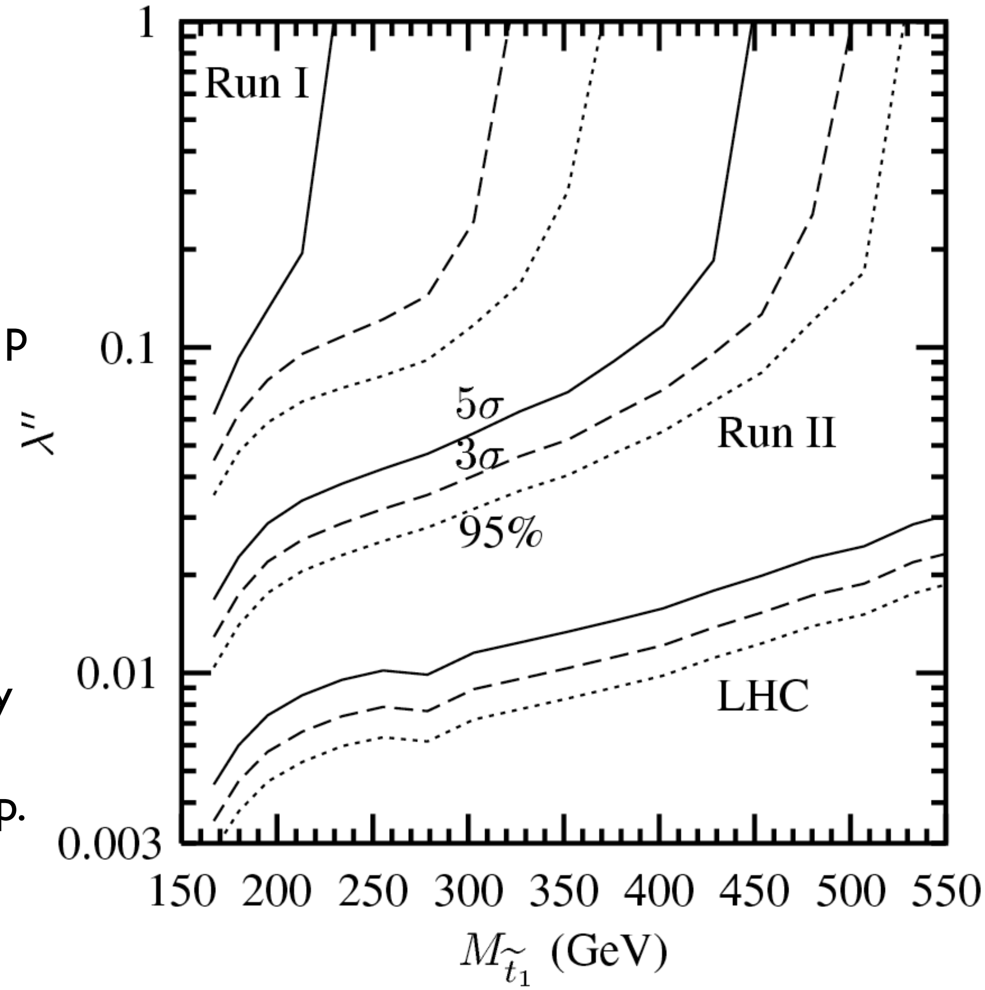
SUSY Higgs

- The MSSM has two Higgs doublets.
  - Because the requirements of supersymmetry don't let us give mass to both up- and down-quarks from the same Higgs.
  - To cancel gauge anomalies from the fermion super-partner of the Higgs.
- When the dust settles, we are left with:
  - One "SM-like Higgs": h^0 (usually the lightest)
  - Two "heavy" neutral Higgses: H^0, A^0
  - A pair of charged Higgses: $H^{\pm}$
- These have very nice signatures, often involving the 3rd generation:
  - $t \rightarrow H^+ b$
  - $H^+ \rightarrow t\, b$, or $\tau^+ \nu$
  - $A^0 bb \rightarrow bbbb$ or $bb\, \tau^+\tau^-$

R-parity Violating SUSY

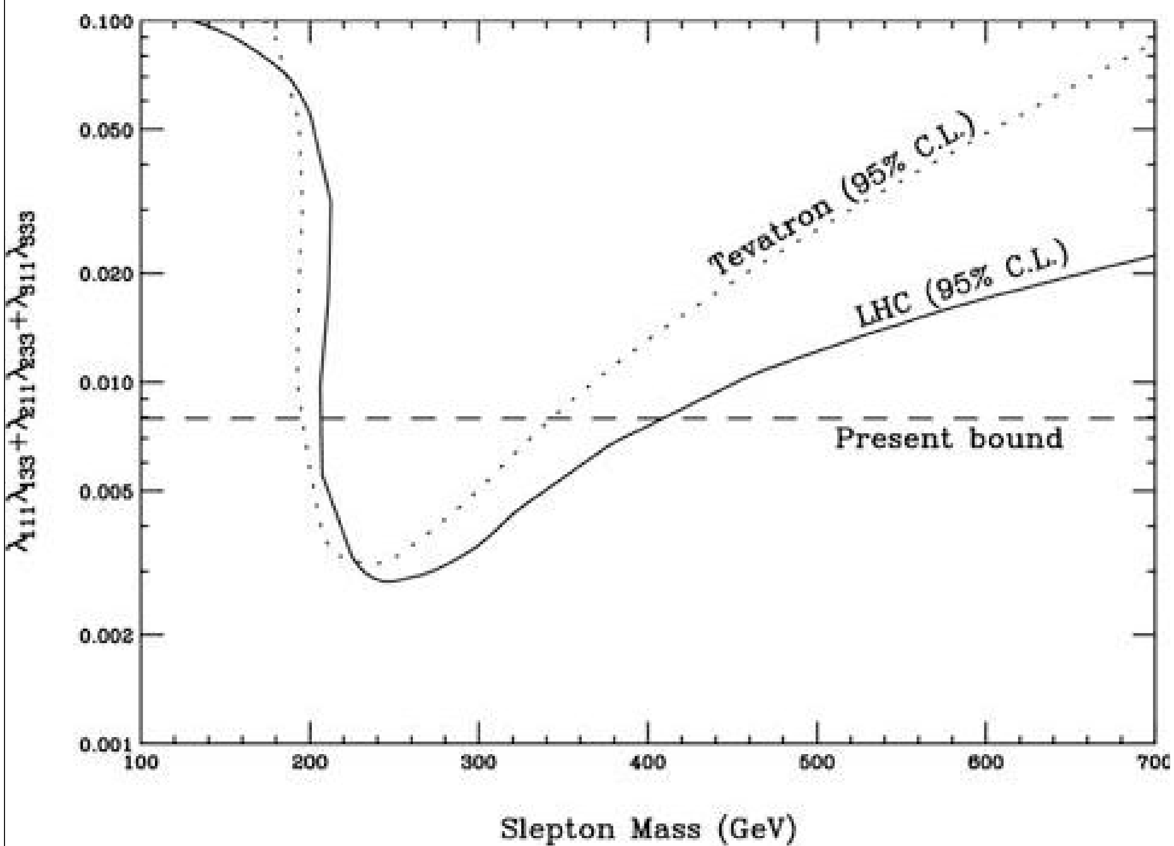
- In SUSY theories, if R-parity is violated, super-partners can contribute at tree level to SM processes such as single top.
- Such interactions generally lead to p decay, constraining their size.
- However, for the 3rd family such bounds are much weaker.
- In this example, there is s-channel stop 'production' followed by decay into top through R-conserving interactions into neutralino and top.



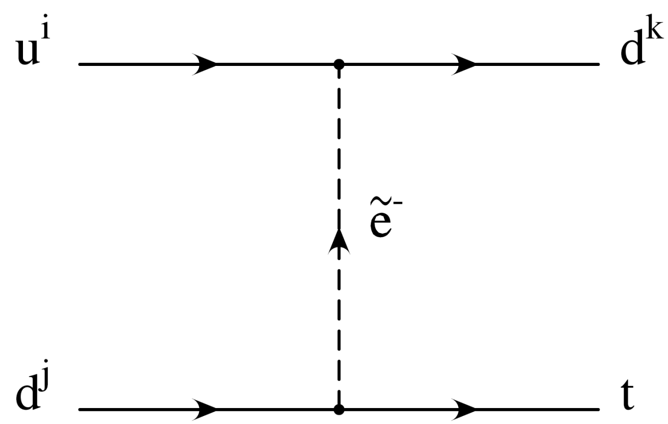


Berger, Harris, Sullivan PRD63,115001 (2001)

$\not{R}$-parity II: Slepton Exchange



R-parity violating interactions which Violate lepton number can produce Single tops through exchange of the Super-partners of leptons (sleptons) In either the s- or t- channels.



Oakes, Whisnant, Yang, Young, Zhang PRD57, 534 (1998)